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EROSION IN LARGE GUN BARRELS

National Materials Advisory Board (NAS-NAE)
Washington, D. C.

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The erosion of gun tubes is a very complex interdisciplinary problem involving several branches of engineering and science. Several mechanisms are responsible for this limitation to gun tube life, some of which are of thermal origin, some are mechanical and some chemical. The exact combination of these mechanisms will depend upon the following components of the gun system.

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EROSION IN LARGE GUN BARRELS

REPORT OF

COMMITTEE ON GUN TUBE EROSION

NATIONAL MATERIALS ADVISORY BOARD
Commission on Sociotechnical Systems
National Research Council

Publication NMAB-321
National Academy of Sciences
Washington, D. C.
1975

NOTICE

The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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ABSTRACT

The erosion of gun tubes is a very complex interdisciplinary problem involving several branches of engineering and science. Several mechanisms are responsible for this limitation to gun tube life, some of which are of thermal origin, some are mechanical and some chemical. The exact combination of these mechanisms will depend upon the following components of the gun system.

1. The gun barrel system
2. The projectile system
3. The charge assembly
4. Wear reducing additives in the propellant
5. Firing conditions

After reviewing the history of gun barrel erosion from these several points of view, possible mechanisms are discussed. Several other fields of engineering endeavors that are limited by severe wear problems are reviewed for possible sources of technology transfer. The report concludes by suggesting long and short range programs, including a number of specific ideas that should be evaluated.

CONTENTS

. I

INTRODUCTION

Confronted with problems associated with the continual upgrading of field guns, reducing the number of different items in supply and lowering overall costs, the Department of the Army has need for improved methods of reducing erosion and extending the wear life of long range cannon. The National Materials Advisory Board was asked to consider all facets of this need and to make recommendations.

OBJECTIVES

The objectives of this report are to make an assessment of the nature of the bore erosion problem; to identify fruitful areas of research; to assess the state of technology of materials and methods in areas which may become significant to gun tubes of improved performance; to suggest experimental techniques, devices, and instruments and methods of reducing data; to enhance the continuing coordination of the activities of the three Services; if feasible, to concentrate on a large weapon such as the 8 inch M110E2 gun system in order to suggest helpful short-range solutions in addition to possible long-range solutions.

DISCUSSION AND RECOMMENDATIONS

While the problem of gun erosion has to some measure been alleviated, there is no implicit assurance that future gun systems will have acceptable wear life. This is particularly true if such systems reach for higher projectile velocities at higher chamber pressure with new propellant formulations. Anticipating that this will surely happen, the need for a better understanding of the mechanism of gun erosion is apparent.

It is evident that erosion of gun tubes is not a simple problem; cutting across the sciences of metallurgy, chemistry, physics, and mechanics. Any future effort should be constructed to recognize the multidisciplinary nature of the problem, both in planning and in direction.

In the course of conducting this task the Committee was impressed by the number of separate and varied investigations and tests that have been performed.

it would probably be fruitful to formally collate and examine the existing data prior to planning further research. This effort might also suggest short-term investigations aimed at quick fixes for immediate problems.

The nature of the gun-erosion problem superficially would appear to be different among the three services. The Air Force is concerned with smaller caliber, high rate of fire, weapons. The Army and Navy have this problem plus larger caliber, high velocity guns and large bore, low performance systems. It is suggested that close liaison between the services would be beneficial. In fact, further effort should recognize that there is a commonality in the problems experienced and the expertise acquired by the three services. Their active participation in future, unified, efforts in this area would be most desirable.

A long-term goal should be a better understanding of the erosion phenomena. It is doubtful that this can be achieved through purely analytical treatment. Rather, any predictive model would be to a large degree empirical. This implies that the various investigators have available valid test vehicles. The extrapolation of data from vented vessel firings, measuring wear of an orifice is open to questions. Much testing has been done in small bore (7.62 to 20mm). It is not at all certain that there is a one-to-one correspondence with these results and those obtained by full-scale firings or that results of various investigators can be translated from one test device to another. A first course of action would be the establishment of a common test device(s). Probably two sizes should be chosen in order to obtain at least first-order estimates of scaling factors.

Assuming a valid test vehicle is available, a parametric investigation of the erosion process should be conducted. The parameters of importance minimally should include propellant chemistry, gun tube metallurgy, projectile materials, and interior ballistic effects. While such a study could not be precisely definitive, because of the complexity of the problem, it could define the role of the leading variables.

The most recent and notable gain in the reduction of erosion has come through the use of additives (talc or TiO_2 in wax) to the propelling charge. While it is generally agreed that the additive is effective because it reduces the heat transfer to the gun tube, the mechanism by which this is accomplished cannot be described at this time. Also, the effectiveness of the additive is not always predictable: cannot be scaled from one gun system to another. Driving towards higher and higher performance systems, one might soon be operating in regimes where the additive is not effective at all. This suggests a research program, in advance of that date, to elucidate the mechanism by which additives reduce erosion. The search for "better additives" without some well developed rationale can result in "one at a time solutions" which must be continually reiterated.

The role of the products of combustion of the propelling charge in gun tube erosion is not well understood. Some work on the effects of specific products and the CO/CO_2 ratio have been performed. The need for higher force constant propellants, e.g., the nitramine compositions, will drastically alter the composition of the propellant products. This suggests the need to support an effort in this area. One can see that superior propellants (i.e., ballistically) might not be useful because of increased gun tube erosion.

Recent advances in polymers and reinforced polymer-fiber composites suggest that the concept of "plastic" rotating bands be reconsidered. There has been some success in demonstrating a reduction in erosion through the use of plastic bands. It is understood that the problem, to date, has been one of guaranteeing the integrity of the band during engraving, travel down the tube and launching from the muzzle. The superior (and more importantly, the ability to tailor) mechanical properties of the newer polymers and composites is certainly worthy of further investigation.

The discussions of other fields of engineering endeavor presented in the sections on technology transfer (Page 41) provide a number of ideas which merit

evaluation for gun barrel use and are recommended to be investigated. In order of ascending difficulty of application, these recommendations are:

1. Insulating and/or Lubricating Sprays or Washes

Mold coatings, or "die slicks," as discussed in the casting and forging technology section, would be simple to introduce to the origin of rifling area as a spray between rounds.

Their effectiveness in extending die life under conditions approaching those met in gun barrels warrants investigation of both proprietary compounds and experimental compounds expressly developed for gun use.

2. Rotating Bands

It is understood that rotating bands are normally made of gilding metal or copper. Copper, by itself, is not noted for its bearing and wear properties. Substituting a copper-lead bearing alloy for the copper might be helpful, particularly since the lead is dispersed throughout the bulk material and is always present for its anti-wear function - even after undergoing engraving. This would clearly entail experimentation with the compounding of the mixture to provide enough lead for "lubrication" and to provide adequate physical properties for rotation. The dispersion of the lead within the copper might offer better resistance to "fouling" than would the alternative of lead plating the exterior of a copper rotating band.

Similarly, the use of aluminum bearing alloys in place of copper merits consideration. Mr. Edward Smith, Delco Maraine Division of General Motors, Dayton, Ohio (phone no. 513-445-4465), is an excellent source of information on bearings alloys and mixtures of both the aluminum and copper-lead varieties.

The sintering process also provides an opportunity for tailoring a "semi-bearing" material specifically for rotating band use. Typical might be a porous iron sintering, impregnated with an appropriate lubricating material.

The behavior (friction, heat generation by deformation, and heat transfer to the barrel) of rotating bands as they are engraved in the forcing cone is amendable to direct measurement and to treatment by well-established extrusion theory.[27] Calorimetry is recommended to establish the heat partition between the shell and the barrel. The coefficient of friction can be calculated by measuring the force required to push shells having rotating bands of two widths. The heat generated by redundant work (in transforming the circular cross-section of the band into the serrated cross-section) can be estimated from relationships developed for metal extrusion.

3. Protective Surface Coatings

As was observed at Watervliet, the arsenal is already deep into the use of hard platings for wear reduction. Chromium-plating and chromium-plating on cobalt have been evaluated and experiments with nickel coatings containing hard particles (like Elnasil) are underway. Tungsten carbide was dismissed as being too brittle and for having poor adhesion.

It is suggested that alloys of tungsten carbide (as used in the Wankel engine) be reconsidered for local application in gun tubes at the origin of rifling. A very thin deposit, plasma sprayed, might require no finishing operations, have minimal internal stress, and offer the best opportunity for good adhesion. The rapid growth of expertise in this field, as stimulated by the Wankel effort, has resulted in new techniques for application and bonding. Mr. Frank Longo, of Metco, is a good source of detail information.

Further toward this end, cutting tool experience has shown thin (0.0002 inch) overlays of titanium carbide or aluminum oxide to greatly enhance the wear resistance of tungsten carbide.

It is also suggested that attention be given to the use of a thin stellite coating at the origin of rifling. Application of this material is an everyday commercial procedure in the manufacture of engine valves. It can be oxy-acetylene sprayed or, for thin coatings, plasma sprayed. Again, Metco is a good source of practical information on these processes.

Another protective coating which might merit investigation is a proprietary DuPont product called "Triballoy." A cobalt-nickel based alloy, it is reportedly very wear-resistant at elevated temperatures and has good hot-hardness capability. Plasma spray is used for application. Dr. Donald Ferriss,

Chief Metallurgist, Triballoy Products of DuPont (302-453-2631), is a source of information on this material and its application.

A key question on the use of any of these hard coatings is whether they would be effective in the gun tube in sprayed layers thin enough to be used without any finishing operations such as grinding or honing.

4. Wear-Resistant Inserts

As has been noted, the use of wear resistant inserts is common in the engine field - cylinder liners, valve seats, etc., and in cutting tools. It is suggested that consideration be given to the use of a permanently installed wear-resistant insert at the origin of rifling. This would permit the continued use of the relatively soft bulk material needed in the tube for fatigue resistance, but provide a harder (at working temperature) material where it is needed for erosion resistance.

Anchoring the insert firmly enough to resist the rotating force imposed by the projectile on the rifling might be handled by furnace brazing the insert into the gun tube during heat treatment of the tube. It is common practice in gear manufacturing to simultaneously furnace braze a pre-carburized insert into a gear and harden it while heat treating the bulk of the gear. Experimental inserts might be anchored in finished tubes by electron beam welding.

Use of an insert opens up a whole new area for material selection . . . including through-hardened steels, carburized and hardened (for compressive stress at surface) steel, die steels, high speed tool steels and others of good properties at high temperatures. Nitriding becomes feasible.

5. Cooling

The drastic decrease in cutting tool life with increased temperatures prompts investigation into means for reducing gun barrel temperatures.

Cooling of the wear surfaces (i.e. the bore) might be accomplished by a jet of expanding gas directed at the origin of rifling between rounds. Or, some cooling might be achieved by appropriate selection of a spray or wash which would also supply the insulating and/or lubricating function of Recommendation #1.

Concluding Remarks

Gun tube erosion can set a limit to the development of more desirable weapons systems. Two things should be done if this limit is to be avoided.

Research drawing on existing technology can provide materials better suited to withstand the severe mechanical, thermal, and chemical environment in a gun tube.

Longer term, more basic studies can develop, at least empirically, predictive models for the erosion process. The ability to predict offers the hope of being able to propose solutions.

The Committee was impressed by the quality of the investigations conducted on the many facets of the gun tube erosion problem in the past. However, it appears obvious that the problem of defining the mechanism of erosion cuts across the missions of the various Army arsenals. It is therefore felt that future effort in this area would be more effective if a single leader and a single source of funding devoted exclusively to this technology area be designated.

DESCRIPTION OF GUN SYSTEM

The components of the gun system included in this report are primarily the gun barrel, the projectile and the propellant charge. Nomenclature is indicated in the first two figures.

A gun barrel for fixed ammunition is shown in Figure 1. Rifling consists of helical grooves cut in the bore of the tube extending from the forcing cone to the muzzle end. The ridges between the grooves are known as lands. The forcing cone includes the origin of rifling where the grooves begin, and the commencement of rifling where the lands reach full height.

Nomenclature for the various regions of projectiles and complete rounds of ammunition is given in Figure 2. In addition cannelures, partially visible under the grommet "O", are ringlike grooves cut in the rotating band in order to lessen the resistance offered to the rifling as the projectile begins to move along the

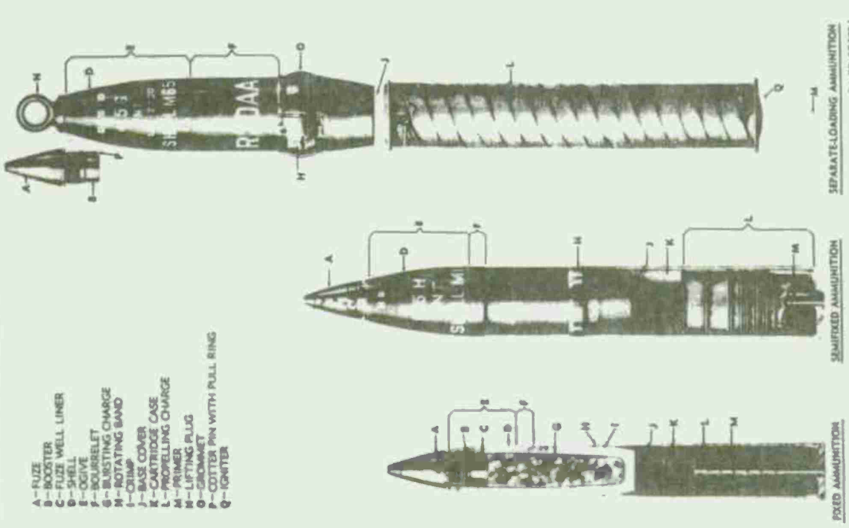


Figure 2 Types of Complete Rounds of Artillery Ammunition

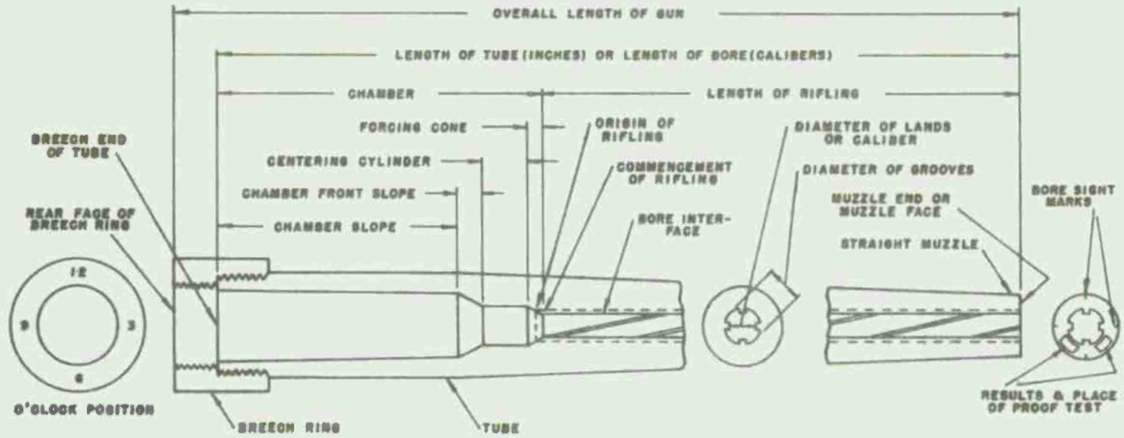


FIGURE 1

NOMENCLATURE FOR INTERIOR AND ENDS OF SOME GUN BARRELS USING FIXED AMMUNITION

WTN.639-814C

gun tube. Also shown in Figure 2 are propellant charges and primers. A round is the short name for all components of ammunitions necessary to fire a gun once.

Erosion is the enlargement and wearing away of the bore interface of gun barrels by the movement of high temperature gases and residues generated from the burning of propellant powder, by chemical action between constituents of propellant powder gases and gun material, and by friction between projectile and bore interface.

Erosion is most often measured by the change in dimensions of the bore. The wear is frequently given as the change in diameter rather than change in radius. Erosion is seldom uniform around the circumference of the bore or along the length of the bore. Especially in large separate loading guns, more erosion tends to occur at the twelve o'clock position in the region of the origin of rifling than at the six o'clock position. Erosion tends to be worst at the vicinity of the origin of rifling and decreases as the distance increases from the origin of rifling until about mid-length. Erosion then begins to increase slightly again as the muzzle end is approached.

If the projectile cants too much, the bourrelet bears on the same group of lands along the entire length of the gun. This may cause eccentric wear of the lands in particular and this is usually very noticeable at the muzzle end.

Erosion has a deleterious effect on the performance of the gun, finally limiting its life. The muzzle velocity, the range, and the accuracy of the weapon are reduced, the variation in muzzle velocity and the variation in range are increased; in extreme cases fuses are damaged and malfunction, also bands on projectiles are stripped. The extent of erosion is sometimes expressed in terms of extent of the drop in muzzle velocity or loss in range. The erosion limited life of guns is the number of rounds of ammunition that can be fired until any one of these characteristics becomes unsuitable for service. It is claimed that in a well designed gun system all these characteristics should reach condemnable limits at about the same number of rounds.

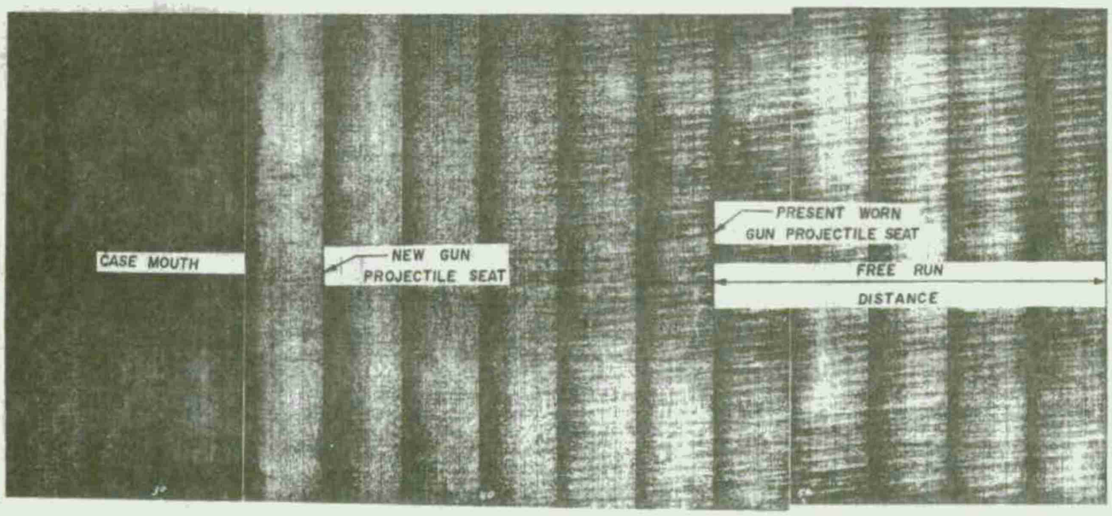
Fatigue considerations affecting life of cannons, and stripping of lands, are not within the context of this report.

HISTORY OF EROSION AND EROSION CONTROL

Erosion is attributed to many chemical, mechanical, physical and thermal occurrances. Very hot gases melt the gun steel and the molten metal is blown away. The constituents of the propellant powder gases react with the steel and diffuse into the metal. Compounds and eutectics of iron are formed. These are brittle and some have low melting points. The transformation temperature of the gun steel is altered and the gamma phase is stabilized at low temperatures. The volume changes of the bore surface metal due to alternate heating and cooling with each round leads to thermal cracking of the interface, so-called heat-checking. The surface of the bore is roughened and friction increases between not only the flowing gases and the gun steel but also the projectile and the barrel. The rotating band wipes off brittle layers, heat softened layers and molten layers. In addition volatile compounds are formed with the steel and carried away by the gases.

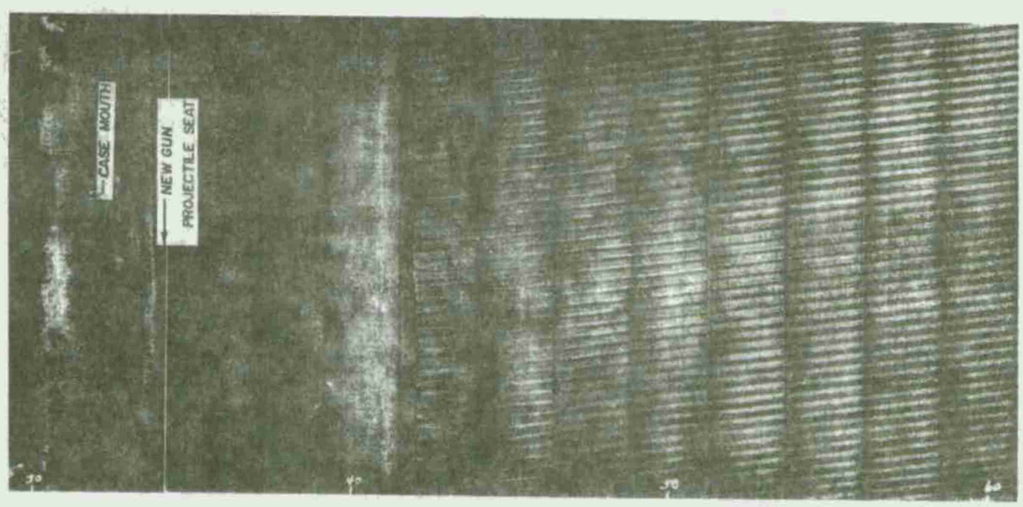
The bore interface of a slightly worn 5" gun and that of an extremely worn 5" gun in the region of the origin of rifling are shown in Figures 3 and 4. The heat check system on lands and grooves is shown in greater detail in Figure 5. The cartridge cases used in these guns act as a rear seal and protect the chamber from the propellant powder gases. In separate loading guns, the walls of the chamber become heat checked. The loss of metal in the vicinity of the forcing cone results in the forward movement of the place where the projectile seats, known as the advance of the forcing cone. There are two consequences, the enlargement of the volume of the chamber, and the increased difficulty to seal the forward end of the chamber against escape of gases because of the roughened and uneven surface. Both of these effects contribute to loss of velocity and range.

The problem is to eliminate or decrease erosion in the vicinity of the origin of rifling without shifting the region of fast erosion to another location.



PHD-0829-4-74 FIGURE 4

5" MK 18-0 S/N 7, AFTER 1500 RDS. OF PYRO.
EXTREMELY WORN GUN



PHD-0828-4-74 FIGURE 3

5"/54 MK 18-4 S/N 565, AFTER 3000 RDS. OF NACO
FIRING SCHEDULE 5 RPM FOR 600 RDS.

WORST CASE NACO WEAR BUT ONLY SLIGHTLY
WORN BY NORMAL STANDARDS.

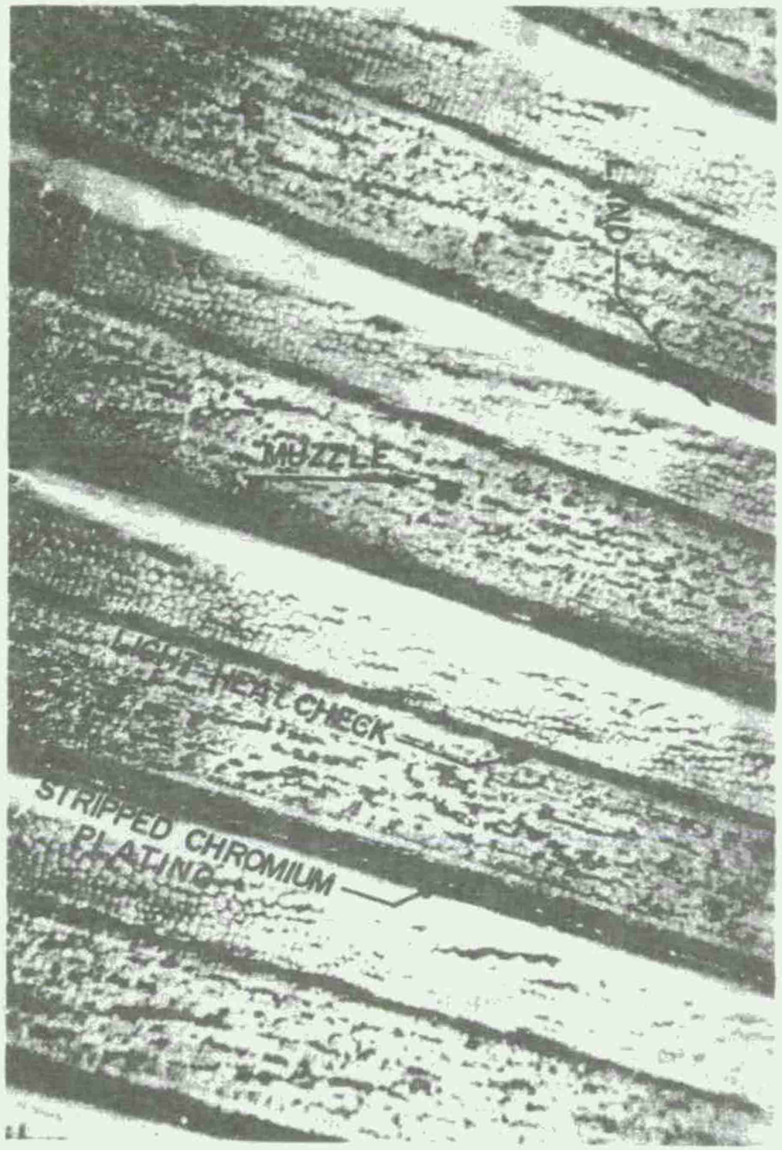


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FIGURE 5

5" MK 18-3 LINER S/N 480
NACO PROPELLANT
8 RPM FOR 600 RDS.

Past approaches to the control of erosion may be grouped under five headings as follows:

1. The Gun Barrel System
2. The Projectile System
3. The Charge Assembly
4. Wear Reducing Additives
5. Firing Conditions

No one is independent of the others.

1. The Gun Barrel System

The material is the important factor in the gun barrel system. Design of rifling, forcing cone and centering cylinder are critical considerations.

The change from cast iron to steel for gun barrels took place over a twenty-year period ending in 1833. Since then the quality, strength and fracture toughness of gun steel have been improved on an industry-wide scale. This improvement still continues today with the introduction of new steel making processes. But the melting point of the gun steel has not changed much.

One important aspect that has not received enough attention is the formation of heat checks on the bore interface and roughening of the surface. Decoppering agents are claimed to increase the rate of growth of these thermal cracks and to increase the rate of wear.[1] The life of a 3 inch trial gun was doubled by eliminating the decoppering additive from the ammunition.

In 1944 during W.W. II, Stellite 21 was developed for machine guns under the auspices of the National Defense Research Council (N.D.R C.) in order to overcome the lack of ductility of Stellite 6 which was found to resist erosion but cracked in testing.[2,3] Stellite 6 was tested along with 18-4-1 high-speed steel and two types of die steel, which three steels were found unsatisfactory. The Stellites were tested especially because of their hot hardness. All efforts to improve Stellite 21 by raising its melting point were fruitless. Failure of the experimental alloys was by cracking.

Stellite 21 liners were successful in the caliber .50 chromium plated and nitrided machine gun barrels. It was not successful in the caliber .60 machine gun, nor in the 37mm gun.

Nickel base hot hard alloys failed because of poor erosion resistance.[1,3] Low and high alloy steels have been evaluated in many different ways for erosion resistance. In general the higher the alloy content, the lower was the resistance, except for low carbon heat treatable intermediate chromium content stainless steels.[1]

It has long been thought that the simplest approach to eliminating erosion would be to use inert metals of high melting point. Four such metals were always selected for trial, namely tungsten, molybdenum, chromium and tantalum. Considerations of cost and availability indicated the use would be as coatings or liners, if at all.[2,3]

Molybdenum base and chromium base hot hard alloys were developed during W.W. II by the N.D.R.C.[2] The resistance to erosion was evaluated as adequate. Following W.W. II the development of these alloys was continued by the Department of Defense.[4,5] After a decade or more of intensive effort no alloy suitable for cannon was developed. The fracture toughness and ductility were inadequate.

"...Alloys containing up to 50% chromium have potentially good ductility in sections up to at least 1.125 in. square when cast as 4-in. or smaller ingots. Above about 40% chromium, the alloys appear to become more sensitive to directional factors, and the best combination of longitudinal and transverse ductility in the high-chromium alloys depended on the amount of reduction during hot working and the method. Generally, ductility increased with increasing amounts of hot reduction, and forging (rather than rolling) gave optimum ductility. Ductility in sections larger than 1.125 in. square appears to require a fine grain size in larger ingots or a method of hot working to refine the grain. The impact transition temperature of a 50% chromium, 50% iron alloy (based on an average of 15 ft-lb. in a standard V-notch Charpy test) was found to be approximately 180°C. (356°F)."[5]

As a result of these characteristics, in spite of a very large program supported by the U.S. Army Ordance Corp. and promising results on laboratory samples, it was not feasible to produce large sections with a fine grain size. Therefore, the ductile/brittle transition temperature was always above ambient. The alloys may have been inherently erosion resistant, but never survived in the gun barrel long enough for one to find out.

Although some liners of Mo base alloys were successfully tested in some machine gun barrels firing long bursts, in others stoppages occurred attributed to chunks of metal being generated by rapid growth of radial cracks in the longitudinal and transverse directions and subsurface cracks in the circumferential direction, and shifting slightly into the bore.

Molybdenum was vapor deposited on steel tubes at 900°C (1650 °F). Adhesion was improved by using a substrate of cobalt 0.00025 inch thick.[6] It is believed that one such tube was test-fired. Under N.D.R.C. auspices much effort was expended to vapor deposit molybdenum at low temperatures. One example was the use of the carbonyl in place of the chloride. Although deposition took place, adhesion was always poor.

Tungsten was not included for test by N.D.R.C. because of considerations of supply.[2] More recently tungsten has been vapor deposited in machine gun barrels at 1300°F (704°C).[1] These barrels showed marked resistance to erosion in experimental firings.

The first usage of chromium on the bore of guns in the Army started as soon as chromium plating became practical. Electrodepositing experiments were started with machine guns. In the 1930s the 3"AA gun liners were chromium plated. The thickness of plate was about 0.0005 inch. No change in bore dimension at the origin of rifling occurred due to firing for about 100 to 200 rounds. After that the rate of erosion was practically normal. But no change in accuracy life was apparent.

Examination of the bore surface of plated and eroded gun liners, and other studies, revealed that the chromium metal was very, although not perfectly, resistant to chemical attack by propellant powder gases. Five modes of failure were evident: 1) in some regions there was poor bonding between the plate and the steel, the plate flaking off quite early in the firing program; 2) there was poor mechanical strength in the surface layers of the steel and plate flaked off with pieces of steel attached to it; 3) at side walls of wide cracks in the steel, there was

deterioration and removal of steel beneath the plate which collapsed for lack of support; through fine cracks in the plate, propellant powder gases reached the steel and chemically reacted with it, causing large areas of deterioration under the plate as well as loss of metal as though by volatilization, also deteriorated areas under adjacent cracks joined to form extended regions where chromium plate had little mechanical support and failed; 4) the plate was heated and softened by the firing, and was easily worn thin at the top of the lands; 5) chromium flaked from itself due to poor mechanical strength within the plated layer.

Using the slit-vent erosion plug test it was shown that adhesion could be markedly improved by electropolishing the bore surface.[7] The minimum amount of metal to be removed from a machined surface was established as 0.002 inch. The same type of test demonstrated that the thicker the chromium plate, the better the erosion resistance, and the less the warping tendency due to heating the substrate steel through its transformation temperature range. Also chromium plate having a Knoop hardness of about 1,000 performed somewhat better than a softer or harder plate.

Firing tests[7] with chromium plated 37mm guns in 1943 and 1944 using double base powder were carried out in order to evaluate the laboratory observations. The thickness of plate used in different test guns ranged from 0.003 inch to 0.010 inch. Standard barrels were used and an amount of metal was removed from the bore by electropolishing corresponding to the thickness of the electrodeposited layer to be tested. It was found that the muzzle velocity of plated barrels was higher than that of companion unplated barrels. This was attributed to reduced bore friction. As long as chromium plate remained on the forcing cone new gun performance was maintained. The advance of the forcing cone in a non-plated gun was slow for about 450 rounds (a measure of life), for about 800 rounds in the guns with a plated layer that was 0.003 inch thick, and for about 1200 rounds in guns having a thicker plated layer. New gun performance over several hundred rounds is considered particularly useful in such weapons as tank guns.

In the period from W.W. II until now chromium plate was used extensively in machine guns and in cannon. There appears to be an optimum thickness of standard chromium plate[3] for each weapon system such as on a 3 inch gun, 0.010 plate was better than 0.005 or 0.020 inch. The softer Low Contraction (L.C.) plate has been tried but the erosion resistance was reduced.[3]

Chromium electrodeposited metal is rich in oxide, in part present in the form of a thin transparent film outlining grain boundaries. The metal is highly stressed and is hard. An extensive crack system exists. In firing, standard plate cracks, the new cracks forming suddenly. Upon heating, electrodeposited chromium has been found to give off gases and to shrink.[5] In one experiment water was given off at about 200° C, hydrogen at about 400° C and shrinkage started to occur about 500° C. Two decades of research failed to find methods of extensively improving the chromium electroplating process-the efficiency of plating, the rate of plating, the elimination of cracks and cracking, the throwing power, the hot hardness, even non-destructive testing for adhesion.

The dependance on chromium plate in some large guns has been reduced by the use of wear-reducing additives in the ammunition, which started in the 1950's with the polyurethane Laminar Coolant and in the 1960's with the titanium dioxide--wax and the talc-wax systems. On the other hand, the wear-reducing additives were not adequate in the 8 in. gun and electroplate may be the alternate method of reducing erosion in this case. Research findings indicate that two layer thick electrodeposits have merit.

Tantalum was tested by N.D.R.C.[2,3] and found to be erosion resistant but had a tendency to crack. Further testing was not undertaken after consideration of cost and supply. Columbium was tested in the late 1950s as an insert and found to be very erosion resistant in machine guns. The metal was hardened by being processed in air. Process control was not found adequate and interest returned to tantalum.

Titanium is not considered to be erosion resistant. Yet experience showed that where erosive conditions were mild, strong titanium alloys served satisfactorily. This experience points to the need for expressing the relative erosion

resistance of materials as an erodibility function involving several degrees of severity of test rather than as a weight loss index determined under a severe erosive test condition.

In summary it would appear that of the refractory metals investigated as coatings or liners chromium has received the strongest emphasis for the longest time, but after considerable development, it no longer presents a significant potential for further improvement. On the other hand molybdenum, tungsten, tantalum and columbium have shown promise and potential but have not been pursued much, probably mostly because of cost, although process control and alloy priority was not as good as now obtainable.

However, cost is a relative term and at some future date performance requirements may be such that in special cases the cost of refractory metals may not be considered excessive, particularly for molybdenum and tungsten which are much cheaper than tantalum and columbium. Since tantalum and columbium alloys can and have been developed with increased strength and hardness and yet retaining considerable ductility, future investigations would probably involve the use of thin liners or inserts of these alloys. Modern methods of internal cladding by explosive bonding might also be applicable to their use in gun barrels.

In contrast, molybdenum and tungsten have very limited ductility for forming operations and therefore have been used experimentally, as CVD* coatings for the gun barrel applications. Most development was aimed at machine gun barrels. Tungsten in particular seems to have the most promise since it was reported effective in reducing erosion without technical problems in application or adherence. The hexafluoride process temperature range, 500-750°C is probably low enough not to seriously affect the structural stability of large gun barrels. The cost of scaling up the process would probably be high but very little is reported in the literature on scaling up CVD processes. A major problem might be in obtaining uniformity of coating thickness along the bore of a large gun barrel.

* Chemical Vapor Deposit

Accordingly, it would be mandatory to evaluate the CVD tungsten coating more definitively before considering scale up. To do this, a small scale but relevant simulation test must be perfected and used both for CVD coatings and for other materials.

2. The Projectile System

For this study attention is focused on the shell and the rotating band.

The bourrelet of the projectile rests and rubs on the lands of the barrel. It is the forward support which helps in centering the projectile. The rotating band of the projectile is the initial rear support which helps in centering the projectile. The relative fits of the front and rear supports and the distance between them are among the several factors which affect the cant of the projectile at start of motion and has an effect on accuracy, range, friction and wear. Increased wear tends to increase the cant of the projectile.

The rotating band of the projectile seats on the forcing cone and seals the chamber so that the propellant powder gases do not escape while pressure is building up sufficiently to start the motion of the projectile. Escape of some gas inevitably happens and leads to erosion. As the projectile moves forward, the rotating band is engraved by the lands, the band material being extruded rearward and sideways into and filling the grooves. Cannelures supply space into which the excess band material can flow without forming fringes and rough edges which would affect the aerodynamic behavior of the projectile. The band rubs on the lands and grooves causing friction and contributing to erosion while at the same time sealing the bore, minimizing the escape of propellant powder gases and rotating the projectile while it passes along the bore.

While extensive studies have been made to explain why wear-reducing additives* function, no simple analysis seems to have been made to try to explain why they do not function adequately in some guns. It is suggested that if there is the possibility of more clearance, particularly at the 12 o'clock position, due to design features, between the seated rotating band and the bore in gun systems which do not respond adequately to the use of wear reducing additives than in those systems which do respond, then much of the additive may be lost with the greater escape of propellant powder gases before the rotating band is completely engraved

* See section 4 descriptive of wear reducing additives.

and the projectile is moving along the bore. A paper study of a few gun systems might be helpful, some which have short erosion life using the wear reducing additive and some which have long erosion life with the additive, comparing matching dimensions of projectile, band and bore particularly forcing cone slope, etc. The potential for undue cant of projectile at time of seating should not be overlooked.

Means of reducing leakage of gases at the origin of rifling have been tried with evidence of reduction of wear.[1] Lips have been placed on the rotating band, shoes or cups made of rubber or plastic have been attached to the rear of the shell, all in order to improve the seal.

Grease has been applied to the rotating band.[1,2] A container filled with silicone oil applied to the rear of the projectile was very beneficial.[6] Such lubricants smear the surface, decreasing friction, and acting as reducers of heat transfer to the bore. Difficulties have included interference with the burning of the propellant.

In order to reduce the access of burning propellant powder gases to the region of the origin of rifling, developmental work with protectors or extensions of the cartridge case have been tried.[1,2] Protectors, the most famous one being the Franklin Institute Small Arms "FISA" protector,[1] were thin steel sleeves over the outside of the neck of the cartridge case and the band of the projectile. The bore of the bore of the gun was altered to give space for the sleeve. The sleeve was extracted with the cartridge case. The erosion was eliminated at the mouth of the cartridge case and at the origin of rifling but was shifted further forward to the end of the sleeve. In cannon using fixed ammunition the cartridge case was extended to cover the band, but the results were similar--a shift in the location of the region of maximum erosion without adequate improvement.

Much attention has been given to the band material following European initiative. Sintered iron bands have been extensively studied. Band pressures and friction were reduced. Wear at the origin of rifling was reduced but replaced

by wear further down the barrel. Soft iron wire rotating bands welded in place have also been studied.

Plastic rotating bands have been tried in both machine guns and cannon and some trials have given encouraging results.[1,8] Wear was reduced at the origin of rifling and muzzle wear was eliminated. The dimensional stability of some plastics has been found to be faulty. High temperature characteristics of plastics affecting their ability to spin reliably the heavy projectiles in hot large guns at high muzzle velocities have not been fully established by the Army. The lack of simple but controlled erosion tests procedures inhibits the establishment of necessary characteristics of plastic products which might be suitable. However, some success has been obtained with plastics in large cannon and it is evident more attention should be given to plastics as a substitute for metal in rotating bands, or for use in combination with metal rotating bands.

3. The Charge Assembly (including additives)

The charge assembly consists of the propellant, the primer, several additives and the container.

Propellants are made of mixtures rather than single constituents. Materials such as nitrocellulose, nitroglycerine, nitroguanidine, etc., are used. The flame temperature is an important characteristic and affects the severity of the erosion. Different propellants having the same flame temperature may cause variations in erosion by a factor of 4. Other aspects important to the mechanisms of erosion are the proportions of the products of combustion in the gases, such as CO, CO_2, H_2O, H_2, N_2, and a wide variety of dissociation products.

Looking first at the heat loss from the propellant gases to the gun tube, Corner[9] gives a semi-empirical formula:

$$\theta = \frac{T_0 - 300}{1.7 + 0.38\, d^{\frac{1}{2}} \left(\frac{d^2}{C}\right)^{0.86}}$$

where

θ = maximum rise in bore temperature above ambient at the origin of rifling, $^\circ K$

d = bore diameter, in.

C = weight of propellant, lbs.

T_0 = flame temperature of the propellant, $^\circ K$

As would be intuitively obvious, higher propellant flame temperature and increased charge weights make for higher gun temperatures. Larger diameter gun tubes run cooler.

Using the above, one may estimate the tube temperature for different systems as shown on Table I on the following page entitled "Calculated Forcing Cone Temperatures."

TABLE I. Calculated Forcing Cone Temperatures.

SYSTEM	8"M110	8"M110E2 Zone 9	8"M110E2 Zone 8	175MM M107	105MM M68
C, lbs/Prop. Type	28.14/M1	43.65/M30	37/M30	57.24/M6	12.09/M30
T_0, °K	2417	3040	3040	2570	3040
d, in	8	8	8	6.9(175MM)	4.13(105MM)
P max, psi	39.6K	39.6K	31K	48.4K	58.5K
θ, °K (calc.)	545	850	800	890	1000
Wear Life (rnds)	>7500	1500*	2700*	1200*	100

* Derived from presentation by Picatinny and Watervliet Arsenals at a meeting of the Committee held at Watervliet Arsenal on July 11 and 12, 1974, and (Proceedings of the Interservice Technical Meeting on: Gun Tube Erosion and Control held 25-26 February, 1970, pp. 1.1-11).

The above is admittedly simplistic and ignores the effect of chamber pressure, tube geometry and chemistry but does illustrate the apparent importance of propellant flame temperature. The issue is also confounded by the fact that the 8" M110E2 and 175MM rounds use the wear reducing additive. Such rounds without additive presumably would have much lesser wear life: such data were not available.

Since for the same muzzle velocity, roughly, the weight of the propellant charge (C) times the force constant of the propellant (F_o) must be the same.

that is: $CF_o = CnRT_o$ = constant

where: F_o = force constant ft lbs/lb

n = gas volume, moles of gas/gm of product

T_o = isochoric flame temperature

R = gas constant

C= weight of charge

Since C is more or less limited by chamber geometry, at least in high performance systems where erosion is a problem, the only avenue open is the development of propellants with lower flame temperatures and lowered mean molecular weight combustion products i.e., the number of moles of gas/gm is increased.

This has been achieved in the triple base cool propellants as shown below:

Propellant	M6	M5	M30
Type	Single base	Double base	Triple base
F_o, (ft lbs/lb)	317000	355000	364000
T_o, °K	2570	3245	3040
n, moles gas/gm	.04432	.03935	.04308
$\bar{M}$, mean molecular weight	22.6	25.4	23.1

Thus M5 would probably be a more erosive propellant than M30 in a given system. While M6 would be less erosive, a larger charge weight would be necessary. Since the systems are generally volume limited M6 could probably not be used.

The development of the "cool" triple base propellants was a significant advance. The requirements for ever higher and higher performance systems however, requires another such step. Currently, in development, the nitramine base systems offer the promise of high force constants, (400,000 ft lbs/lb) and low flame temperatures (approaching 2500°K). The mean molecular weight of the gases is less than 18 in some instances. There is some evidence from vented vessel firings, measuring wear in a nozzle, that these propellants are more erosive than the current standard formulations. One explanation that has been advanced is that the particulate nitramine in the propellant is acting as an abrasive. However, in the less erosive triple base propellants, a significant fraction of the formulation is particulate nitroguanidine. This would seem to question this interpretation of the increased erosivity. Also the additives, like TiO_2, are not considered abrasive.

It would seem that the chemistry of the combustion gases of the nitramine formulations might be of some significance with regard to the increased erosivity. Evans et al,[10] using a vented vessel, investigated the effect of the CO/CO_2 ratio with added trace amounts of other gases. They were able to demonstrate an increase in erosivity due to reduced CO/CO_2 ratios. The severity of the effect increased with increasing temperature. It is also interesting to note that Lenchitz and Silvestro[11] report that the various additive formulations increased the CO/CO_2 ratio when added to a propellant fired in a bomb calorimeter. Particularly interesting (Evans) is the observation that hydrogen in low concentrations, increases the rate of erosion. They postulate the formation of volatile iron carbonyl catalyzed by the addition of hydrogen. It is interesting to note that the lower mean molecular weights of the product gases of the nitramine propellant combustion is, in part, due to higher hydrogen concentrations. Thus, one could

suggest that while the erosion mechanism at high flame temperatures is principally thermal, at lower flame temperatures, the change in product gases may make the chemistry the first order cause.

The CO/CO_2 ratio and the iron carbonyl mechanism have also been investigated by Frazer.[12, 13]

Contributing to the chemical species in the propellant powder gases are the products from the primer which consists usually of black powder (carbon, sulfur, and potassium or sodium nitrate) and the percussion element which may be mixtures of mercury fulminate, potassium chlorate, antimony sulfide, and lead styphnate. Such compounds and their combustion products act as catalysts to chemical reactions between gun steel and hot propellant powder gases.

Among the reaction products which have been identified are iron carbide, two iron oxides, two iron nitrides, iron sulfide, copper sulfides, zinc sulfides, chromium carbide, nickel carbide, stable austenite, iron carbonyl. Iron carbide and iron oxides form low melting point eutectics. There are many iron carbonyls some of which are volatile and decompose readily with slight heat to form carbides, oxides, carbon, etc. In one investigation enough carbonyl was recovered after rapid cooling of propellant powder gases to account directly for 0.03% of the weight loss of the barrel, and it was estimated after taking into account the decomposition products that half of the weight loss of the gun could be attributed to this carbonyl reaction. Evidence of the loss of gun steel by some volatile process is found in the metallographic study of the bore interface of worn plated gun barrels.

The CO/CO_2 ratio is higher[2] in the combustion products of single base cool propellants than it is in the double base (hotter) propellants.

A deep understanding of the role of the propellant in gun tube erosion is not a trivial problem. The hydrodynamics, heat transfer, and chemical kinetics individually are not readily amenable to analytical or experimental treatment. Coupling of these descriptions as a unified "erosion" model represents a formidable challenge. Higher performance gun systems (higher muzzle velocities and chamber pressures) can be expected to be more subject to tube erosion. An understanding of the mechanism of erosion should point to a relief from the problem. It would seem that this task, as a multidisciplinary effort, should be a matter of high priority, and should begin as soon as possible; in anticipation of future user requirements.

In the short term the nitramine propellants with their lower flame temperatures seem to offer some hope. It is not clear that they are all more erosive. (It is known that the Air Force is involved in this research area. No data from this source was available at this writing). Perhaps trade-off's in formulation are possible which will be acceptable in terms of erosion but which do not yet yield the full potential of the nitramine compositions.

Additives which are incorporated within the propellant powder, in order to retard deterioration in storage are diphenylamine, ethyl centralite, etc. The additive commonly used to suppress muzzle flash is potassium sulfate.

Additives which are not incorporated within the powder, but may be included in the ammunition are the decoppering agent (usually lead foil) and wear additives. Reference has previously been made to the decoppering agent accentuating roughness of the bore and increased wear, and to potential catalytic actions of black powder and potassium sulfate.

It was first noted that there was considerable difference in the wear rate, (at the origin of rifling), between guns in which the propellant charge was contained in a cloth bag versus those in which the charge was in a metal cartridge case. The "cartridge case" gun wore faster. This was attributed to the cool gases from the pyrolysis of the cloth bag flowing in a laminar layer down the gun tube for a few calibers. This presumably served to insulate the origin of rifling from the high temperature gases generated by the propellant combustion.

This was extended by the British to placing a silicone oil filled tampon on the base of the projectile. In moving down the tube oil was smeared on the tube surfaces to insulate it from the hot gases. Reduction in erosion was observed.

The Canadians[15] applied the laminar cooling effect to cartridge case rounds by a polyvinyl chloride or polyurethane foam jacket placed in the forward portion of the case. This served to reduce the rate of erosion by a factor of about 2-3.

The effort in the U.S. centered about the use of the "Swedish additive".[16] As finally applied, it consisted of a mixture of TiO_2 and paraffin wax coated on cloth. A scroll of this material was placed immediately to the rear of the projectile in the cartridge case. Extension of the wear life of gun tubes was remarkable. For example, in the 105 mm gun with the M392 ADPS round the useful wear life of the tube was reported as extended from 100 to 10,000 rounds. In other systems the effect was not so marked e.g. the increase in the 90 mm systems was a factor of three, (700 to 2100 rounds). One is unable, to date, to predict the degree of success of wear reducing additives in a particular gun system.

Picard[17] extended the "Swedish additive" concept to include materials other than TiO_2. The preferred material is a very fine talc, again dispersed in a wax matrix on cloth and applied in a similar fashion. In certain guns this appears to be more effective than TiO_2. That this is true in all guns is uncertain.

There is evidence from vented vessel firings (measuring orifice wear) that wax alone is an effective material. This has led some to comment that the principal function of the particulate material (TiO_2 or talc) is to provide stress risers to assist the wax in breaking up upon firing the charge. This does not seem to fit with the specification expressed in the above quoted patents to use the lower melting point waxes; presuming that the lower range melting points would represent more "plastic" waxes, less prone to "shattering."

It should also be noted that the particulate matter alone, without the presence of the wax, can effect a reduction in wear in some situations. It is reported (unconfirmed) that in the 40 mm grenade launcher the TiO_2 or talc/wax combination did not prevent erosion. Yet a small amount of talc (?) contained in a plastic packet was effective. The launcher is a hi-low type system where the propelling charge is burned at high pressure in a "chamber" built into the cartridge case. The hot gases are then vented through a pair of orifices at low pressure into the space behind the projectile.

The patents of Jacobson imply that the particulate matter and the matrix in which it is contained affect the efficiency of the additive. The inorganic particles reported were: $Na_2B_4O_3$, Na_2WO_4, $Cr(NO_3)_3$, CrF_3, MoO_3, $AlF_3 \cdot 3H_2O$, WO_3, Ta_2O_5 and TiO_2.

The reduction in wear amounted to 25 percent for the $Na_2B_4O_3$ to greater than 95 percent for WO_3, Ta_2O_5 and TiO_2, in the order shown. The issue is confounded by the method of application: various substrates ranging from sheets or propellant, paint, dispersed as a powder, or contained in a layer of paraffin wax near the mouth of the case. This latter method used, with the WO_3, Ta_2O_5 and TiO_2, was the most effective. The work at Picatinny Arsenal investigated the use of Group IV oxides as the particulate matter in a wax matrix. Silica (SiO_2) was found to be the most effective. This was attributed to its large surface area and high heat capacity. Smaller particle sizes (200u) were preferred. The Picard patents specify particles sizes 3 to 60 μ. No mention is made of particle size in the Jacobson patent.

The Navy[18], as late as 1969, appeared to favor the use of polyurethane cylinder as a wear reducing additive. However, recent data[19] has shown talc to be superior for use in 5"/54 guns. Navy data also imply that a residual wear reducing effect persists when rounds with additive are followed by non-additive rounds.

Experience, measuring the wear of an orifice in a vented vessel and firing propellant-additive mixes i.e., without wax, may be summarized as follows:

> The reduction in wear is inversely proportional to the particle density and directly proportional to the thermal diffusivity.
>
> The additive should be segregated from the bulk of the propellant and placed in the forward part of the charge. No effect of particle size could be demonstrated.
>
> Phenolic microballons (50 μ diam) were almost as effective as the smallest talc particles: the best additive.

These results were derived from a series of tests designed to verify the thesis that the particulate matter acted to damp the turbulence. In so doing, they would cause the laminar layer, an effective barrier to hear transfer, to become thicker. The validity of this supposition was not demonstrated.

It is evident that there is a large body of information concerning control of gun tube erosion using additives. These data apparently have never been collated and examined with a view to developing a rationale for understanding the phenomena. The main thrust of the research and development effort has been the development of better additives. Yet "better" additives have not been universally successful. It is submitted that an attempt should be made to elucidate, in depth, the mechanism by which additives reduce erosion. This appears to be necessary in anticipation of future requirements for high performance gun systems possibly using exotic propellants.

There does not appear to be any short-term solution. "Quick fixes," i.e., variations on the current theme, will probably continue to have some measure of success.

4. The Firing Conditions

The firing conditions have an effect upon erosion. Two temperature systems are significant, namely the temperature of the bore interface and the temperature of the wall of the barrel. Neither is independant of the other.

Since W.W. II extensive studies have expanded the understanding of barrel heating. Much can now be predicted and when needed useful equipment is available. Reference has already been made to the interdependence of flame temperature of the propellant powder and the temperature of the bore interface. The rate of fire is also an important factor and it has several parameters, namely number of rounds per minute (rpm); number of rounds in the burst of fire; number of bursts; time between bursts; time between repetitions of cycle before complete cooling of weapon to ambient temperature.

The number of parameters add to the complexities of standardizing erosion testing of any one model especially since large guns are being used in substained firing programs.

A high rate of fire raises the temperature that the bore interface can reach and presumably can at times overcome the benefits of cool propellants. The converse is also true that cool propellants can permit high rates of fire to be tolerated. But it follows that hot hardness and the retention of hot hardness after cycles of heating and cooling are two more parameters to be included in considerations of new materials for erosion resistance.

MECHANISMS OF GUN BARREL EROSION

The erosion of the barrel of a gun is an unusually complex interdisciplinary problem because it is influenced by the design parameters of all elements of the gun system: those of the barrel, the projectile, and the propellant. In addition, it is influenced by the rate of firing.

A gun barrel is subject to

- high temperatures and temperature gradients
- high pressures
- reactive gases
- thermal and mechanical shock
- cyclic stresses of thermal and mechanical origin
- high gas velocities
- high velocity sliding contact

This gives rise to a large number of possible mechanisms for the loss of material generally referred to as gun barrel erosion. The problem is unusually difficult because the chief mechanism or combination of mechanisms undoubtedly changes when any of the elements of the gun system are changed, such as the size or range of the gun. The problem is further compounded by the fact that most of the erosion mechanisms will not act independently but will interact with each other.

Possible gun barrel erosion mechanisms may be conveniently divided into the following three types: thermal, mechanical and chemical. Table 1 lists a number of examples of each type.

Thermal
- Structural Change (including thermal softening)
- Loss of residual stress
- Surface melting
- Ablation

Mechanical
- Erosion (by gas flow or solid particles)
- Abrasion
- Attritious wear
- Surface fatigue
- Brittle microfracture

Chemical
- Reaction with hot gases
- Oxidation
- Carburization or decarburization
- Diffusion alloying

Surface temperatures in many applications will be sufficiently high to cause thermal softening and a loss of residual stress from a thin layer of metal at the surface. A thin surface layer may even transform to austenite and the soft austenitic material may persist after firing if the cooling rate is sufficiently high. Melting and ablation probably do not occur with the original steel but could result following a chemical change. For example, there is evidence that some of the copper rotating band transfers to the rifling and then alloys with iron to form a material on the surface capable of melting. This action is sometimes prevented by the incorporation of sheet lead in the propellent charge which acts as a decoppering agent. There is also evidence that iron reacts with CO in the combustion gas to form iron carbonyl (FeCO) which is volatile enough to ablate. This reaction is influenced by the CO/CO_2 ratio which in turn is influenced by the presence of H_2S, SO_2, NH_3, H_2, NO in the combustion gases.

Hot gases move down the barrel of a gun at velocities that are sufficiently high to scour metal from the surface, particularly if the surface is in a thermally softened state. The entrainment of solid particles of combustion or of solid wear particles in the high velocity gas stream will augment the gas erosion process. The projectile is in solid sliding contact with the barrel as it moves forward and

this can lead to abrasive (large particle) or attritious (small particle) wear if lubrication is not sufficient. The cyclic thermal and mechanical stresses that result each time a gun is fired can lead to the formation of microcracks in the surface which can join up to produce relatively large wear particles which themselves then do further damage. This is apparently the situation when some gun barrels are given a thin (.001-.003) surface coating of hard chrome plate. Wear particles may also be generated by single-blow impact if a brittle surface layer results from a chemical reaction between the hot gases and the metal surface. These are further examples of interactions involving both mechanical and chemical mechanisms.

Summerfield's study of gun damage resulting from the burning through of aluminum cartridge cases[19] is indicative of one aspect of the erosion problem.

In addition to carbonyl formation, other chemical reactions that are possible in a gun barrel are oxidation, carburization, nitridation and sulfurization. These may take place on the surface or at the tips of microcracks that are of thermal or mechanical origin. When such chemical action is present in combination with high surface stresses, stress corrosion cracking may occur.

Because of the complexity of the problem and the fact that it involves so many mechanisms a universal solution does not appear likely. The best that can be hoped for is the possibility of identifying the principal type of erosion (thermal, mechanical or chemical) for a given gun system and then subsequently changing those items having the greatest influence on that type of difficulty. If temperature is demonstrated to be the nature of the problem then possible sources of improvement would involve improved additives, a cooler burning propellant, spray internal cooling following firing or by use of a more refractory material in the form of an improved material, a sleeve or a coating applied at the breech end or throughout the length of the barrel.

If the difficulty is expected to be largely mechanical in nature this might be identified by comparing erosion results for a high-melting, non-transforming, strong material with the standard material, such as one of the refractory metals, even though the material cannot be used in practice. Having demonstrated the character of the difficulty it would then be possible to explore a number of alternatives that would improve mechanical behavior of the barrel surface, such as use of sleeves or electrolytically or vapor phase deposited coatings.

If chemical action is thought to be the source of the difficulty this might be demonstrated by introducing an ingredient into the propellant charge known to increase chemical action, and noting the relative change in the rate of erosion.

Tests such as those just described should be run on the full scale prototype system, since at the present time it does not appear possible to translate model studies into those for a full scale gun system. At the same time however, it would be useful to perform a series of model studies in order to screen new potentially useful additives, lubricants, or coating materials. These model studies should also provide an understanding as to the nature of the action involved with a given change. For example, the action (or actions) of additives are presently not known with sufficient certainty. The wax is thought to coat the barrel to prevent heat transfer while the inorganic ingredient (SiO_2, TiO_2, Talc) has been variously described as a heat absorber, a heat reflector or shield, a strengthening agent for the wax or a dispersing agent for the wax. One thing that seems clear is that the finer the degree of subdivision of the inorganic material the better. It is important that we have a clearer understanding of what an additive does that is useful so that we can estimate the degree of improvement possible and hence more quickly optimize the performance of additives. Model tests on a small bore gun system would appear to be of value for such purposes.

A relatively small bore gun system should be adopted for use by the Army and Navy for long range model studies covering all three types of erosion. The purpose of this work would be to provide a better understanding of the fundamentals

of gun barrel erosion. This work should be carefully coordinated by an interservice gun barrel erosion committee with some non-government representation for breadth. The full scale tests that will always be essential to characterize and correct specific gun barrel erosion difficulties would constitute the short range portion of the program.

TRANSFER OF TECHNOLOGY FROM OTHER FIELDS TO THE EROSION OF GUN BARRELS

The "Wear", referred to in this report, is a collective term for a number of phenomena capable of creating dimensional changes and includes mechanical wear (adhesion, plowing, abrasion), erosion by swiftly flowing gases, corrosion by the products of combustion, and surface cracking or deterioration due to thermal shock or thermal fatigue. Similar destructive phenomena limit the useful life of internal combustion engines, metal cutting tools and the dies used for forming metal in the casting, forging and extrusion processes.

Discussion of wear problems in each of these fields follows, as does a summary of those corrective measures used in each area which might also be applicable to gun barrel use.

1. Internal Combustion Engine Technology

While there are functional similarities between an engine piston and a projectile, a piston ring and a rotating band, or a cylinder barrel and a gun tube -- the magnitudes of pressure and temperature in the gun are far more extreme. This, plus the continuous presence of lubrication in the engine, makes direct comparison difficult. There are, notwithstanding, a few critical areas which may relate to the gun problem.

Exhaust valves in four-cycle engines are exposed to high combustion chamber temperatures while closed (3000 degrees F., or more). At the moment the valve opens by lifting off its seat, combustion products at high temperature flow over the sealing edges of valve and seat at sonic velocity - circa 1600 feet per second in a typical case.

This may be analogous to the flow of propellent gas around the origin of rifling prior to the time that engraving of the rotating band effects a seal.

In the case of the engine, the combined actions of the hot gas flow and the mechanical hammering or pounding of the valve on the seat result in dimensional changes in both parts. Gas erosion, corrosion, oxidation and mechanical wear are all thought to play a part.

Erosion of the valve itself has traditionally been the prime source of concern. The valve, as a result of its mushroom shape and the fact that it is constantly in motion is very difficult to cool effectively, and hence, operates at higher temperature than the seat. Local erosion or "guttering" of the sealing rim of the valve can produce massive leakage of gases from the cylinder, rendering the engine unuseable in few operating hours.

Steps taken by engine designers to minimize the problem include cooling of the valve, selection of valve materials with good physical properties and high corrosive resistance at elevated temperatures, and protective coatings for the sealing surface.

Cooling of the valve in engines of moderate specific output (horsepower developed per unit of piston displacement) is limited to supplying ample coolant around the valve guide (in which the valve stem reciprocates) and the valve seat (with which the sealing face of the valve makes intermittent contact) to remove heat from the valve through conduction. In higher output engines, the valve may be hollow and partially filled with sodium. In use, the sodium melts and sloshes to and fro in the valve to conduct heat from the head to the cooler stem portion.

Valve materials are austenitic steel alloys of chrome, nickel and manganese. Typical are 214N (containing 21% chromium, 4% nickel and 9% manganese) and 2155N (21% chromium, 5% nickel, 5% manganese).

Over the years a wide variety of protective coatings has been used on the sealing face of the valve but the accepted standard for severe applications is a Stellite facing, applied by "puddling", a form of welding.

The valve seat, formed in a mass of relatively well-cooled metal, is less prone to catastrophic "guttering" or "burning" than the valve itself. In typical automotive use, for instance, the grey cast iron of the cylinder head has long been adequate as a seat material and the seat is simply machined into the iron.

The wear or erosion of the seat typically appears as a gradual recession or sinking of the seat into the bulk material of the cylinder head. The geometry of the sealing face is maintained and negligible leakage occurs during the process. This recession continues at a slow pace until it causes the valve motion to be stopped by the valve driving linkage rather than by the seat - or, in other words, until the valve stands slightly open during the period when it should be closed. A high rate of leakage then occurs.

As noted above, the rate of recession of the valve seat in automotive applications has long been very low. Recently, the trend toward "no lead" gasoline has changed the picture markedly.

Commercial gasolines have long contained tetraethyl lead as an octane improver and engines were developed on that basis. Recent emphasis on exhaust emission reduction has necessitated use of catalytic converters in the exhaust systems. The lead compounds were found to poison the catalysts, hence it was decreed that fuel must be made available which was free of lead compounds.

It was soon noted that engines using the lead-free fuel suffered early failure from valve seat recession. The nature of the recession was similar to that found with leaded fuel, but the rate of recession was far greater - perhaps a factor of 10-15 times greater.

The mechanism by which the tetraethyl lead protects the valve seat is not fully clear, although best opinion is that lead oxides serve as an anti-welding agent to reduce metal transfer when the valve contacts the seat.

Whatever the mechanism, steps taken to regain the valve seat life when using the no-lead fuels have concentrated on material changes in the seat. Hardening of the integrally-machined iron seats (induction hardening) has been helpful in engines of moderate specific output. For high-output or heavy-duty applications, it has been necessary to use valve seats of superior materials inserted into the cast iron cylinder heads. Typical of such insert materials are high chromium and nickel irons (20% chromium). In some cases the sealing faces of the seats are stellite-coated, by welding or oxy-acetylene spraying.

Piston rings in an engine are somewhat analogous to the rotating bands of projectiles in that they must seal the expanding gases resulting from combustion of fuel (propellant) while sliding with the piston (projectile) along the cylinder (gun bore). On the other hand, they are not subjected to the plastic flow suffered by a rotating band and are provided with a reasonably good supply of lubricant on each stroke.

Sliding, as they do, at mean velocities of up to 4000 feet per minute while reversing direction at up to 20,000 times per minute, sealing pressures ranging

up to 2000 psi at sealing surface temperatures of 600-800 degrees F., modern piston rings are remarkable in resisting wear to the extent that they do.

Again, the materials of the sliding surfaces are critical. The cylinder walls are almost universally of gray cast iron at a hardness of 200-240 Brinell with an initial surface finish of 15 to 20 microinches RMS. There are exceptions. The piston-type aircraft engines used steel sleeves held in aluminum housings, with the steel often nitrided or chromium-plated. Small air-cooled engines sometimes use aluminum cylinders with chromium-plated bore surfaces. The Chevrolet Vega automobile engine block is cast of high-silicon aluminum alloy and the piston rings run on the aluminum surface - which has been electro-etched to make the silicon particles protrude microscopically above the aluminum. Cast iron, however, is the norm.

Piston rings are usually cast of iron or, more recently, formed and sintered of iron powder. Again, protective coatings are common. Tin plating is used to provide anti-scuffing protection, particularly during the run-in period. Chromium-plating is common for heavy-duty applications. Similarly, molybdenum disulphide coatings are effective in extreme cases.

Wankel engine apex seal development provides an additional case where technology might be transferred to help solve the gun barrel erosion problem. Here sealing between the apexes of the triangular rotor (piston) and the "bore" of the trochoidal rotor housing (cylinder) is accomplished by a single seal head in contact with the housing surface by spring.

Normal piston ring technology is not applicable. Wear conditions are severe and have not yielded to numerous attempts at analytical solutions. Edisonian research has evolved several workable combinations of seal and trochoid housing surface.

One, which has had some commercial success (Toyo Kogyo Mazda automobile) uses a hard chromium-plated trochoid housing and seals made of a highly

proprietary carbon compound containing aluminum particles. Pulse-plating processes (Novachrome, for example) are common.

Another (NSU Ro 80 automobile) is based upon an Elnasil-coated trochoid housing with apex seals of an iron compound akin to piston ring material (Goetze-werke's IKA). Elnasil is a plating process which provides a matrix of nickel containing particles of silicon carbide.

For high-output or heavy-duty applications (marine applications, for example), best results have been obtained with a coating of tungsten carbide on the trochoid housing and seals of tool steel.

The "tungsten carbide" is a mixture of tungsten carbide, nickel, cobalt and alumina applied by spraying with a plasma gun. This material is proprietary and is made by Metco, of Westbury, Long Island, New York...as is the plasma gun.

A typical application uses Metco 439 alloy, plasma-sprayed to a thickness of not more than 0.015 inch to minimize internal stress. This is ground to a thickness of 0.005 to 0.010 and honed to the desired surface finish.

Remarkable progress has been made in the last 12-18 months in evolving tungsten carbide coating of superior adhesion characteristics and minimum cracking propensity.

Engine bearings are designed for use with ample quantities of oil as a lubricant. They must, however, cope with transient or emergency situations where they operate for brief periods in the regime of boundary lubrication or even under conditions of dry friction.

Toward this end, multi-material bearings have been devised and used to good effect. During World War II the use of silver-lead-indium bearings was common in aircraft engines. The silver was plated onto a steel shell or backing to a thickness of .020 to 0.030 inch, providing good heat conducting and fatigue resistance. A 0.001 to 0.003 inch layer of lead plated over the silver offered

resistance to scoring and provided some degree of embeddability for small particles. A very thin layer of indium protected the lead from the corrosive action of the lubricating oil and its content of combustion products.

While cost and availability have led to the demise of the silver-lead-indium bearing for most applications, thin plated layers of silver are currently used as a solid lubricant in critical operations.

For example, the side faces of roller-bearing connecting rods used in two-cycle engines are so plated (about 0.001 inch thick), as are the bearing cages or retainers used in such applications. The silver makes the difference between satisfactory operation and failure.

A current substitute for the silver-lead-indium bearing is the copper-lead bearing. Here the bearing is a mixture - not an alloy - of copper and lead with the lead dispersed throughout the copper. A typical mix might contain one-third lead, two-thirds copper, with a trace of tin or silver to increase the hardness. Bearings of this type have excellent wear characteristics under extreme conditions as the lead forms a low-friction layer on the surface which is self-replenishing.

Such mixtures can be cast or sintered. In casting, the resulting structure is a matrix of dendritic copper with the lead mechanically filling the interstices. For sintered material, a porous copper matrix is first formed by sintering and then impregnated with lead.

Aluminum has also moved into the bearing field, generally alloyed with cadmium and often containing tin, nickel, or silicon in the form of deliberate "inclusions." Typical are Federal Mogul's AT6 material and G. M.'s Moraine 410. They can be either cast or wrought.

Traditionally, engine wear is determined by disassembling the engine after running and measuring the individual parts with conventional measuring tools - micrometers, dial bore gages, etc.

Engine cylinders present a problem in that permanent distortion of the bore ("out-of-round") is frequently greater than actual wear, thus making measurement of bore wear impossible. During World War II, Mr. S.A. McKee of the National Bureau of Standards devised a method for measuring wear without regard to distortion.[20]

The McKee technique involves indenting the wear surface, prior to starting the test, with a diamond penetrator akin to an oversize Knoop hardness penetrator. By observing the reduction in length of the pyramidal indentation as wear proceeds, one can easily compute the depth of wear from the known geometry of the penetrator. The geometry of the Knoop indentor is such that the change in the pyramidal length is approximately 30 times the radial depth of the layer.

Special tools for applying the penetrator to the surfaces of cylinder bores and periscopic optical devises for reading the dimensions of the indentations were devised and marketed during World War II and were widely used in engine laboratories at that time.

The same basic technique has since been used in laboratory work on the nature of the wear process, using simply a Knoop diamond and a measuring microscope to measure very small amounts of wear in bench tests.

An application of this technique to the wear of gun barrels is questionable as the scuffing, smearing and other plastic deformation involved will tend to fill the indentation with debris and obscure any measurement of real wear.

2. Cutting Tool Technology

High temperature (1000 F. and higher) and pressures (100,000 psi and higher) exist on the face of a metal cutting tool. In addition, a clean freshly generated surface passes across the face of the tool at high speed. These conditions result in interaction between chip and tool which in turn results in rapid wear. Review of this technology should be useful in providing clues to solutions that might prove successful in reducing gun barrel erosion.

To withstand such extreme conditions, cutting tools must be refractory enough to retain their shape under high operating temperatures, hard enough to resist the erosive action of the chip and ductile enough to avoid chipping when microwelds which form on the tool face are broken. Material characteristics that are useful in prolonging tool life should be useful in preventing gun barrel erosion.

High speed steels that contain substantial amounts of tungsten or molybdenum to increase the hot hardness of the tool are far superior to ordinary alloy steels and such materials might be useful as inserts at the breech end of a gun. Where increased abrasion resistance is called for increased amounts of chromium and vanadium are added to provide hard complex carbides. Increased amounts of cobalt are employed to increase the hot hardness of a tool steel. Cemented tungsten carbides and hot pressed ceramics are still more refractory materials but suffer from an increased tendency to chip. If such materials were to be used in a gun barrel they would have to be in the form of spray coatings. The lack of ductility of the coating would then be largely offset by that of the underlying steel.

Recently, the crater resistance of tungsten carbide tools has been substantially increased by the vapor phase deposition of small amounts (0.0002 inch) of titanium carbide or aluminum oxide on the surfaces of tungsten carbide tools. These materials are more stable than tungsten carbide when operating in contact with the thin layer of austenite that forms on the surface of a chip. Although titanium carbide and aluminum oxide are too brittle to be used in bulk, they have sufficient ductility when used as a very thin overlay. These surface coatings

diffuse into the tool face ahead of the wear zone and hence are effective in decreasing the rate of wear to depths that are far greater than the thickness of the layer initially applied. If tungsten carbide coatings are used in gun barrels it should be useful to employ thin coatings of titanium carbide or aluminum oxide to the tungsten carbide to further increase wear resistance.

A CVD coating of titanium carbide has been found effective also in reducing erosion of steel compressor blading for helicopter gas turbines, even though the fatigue resistance of the steel blading was reduced. Although only 0.0002" is used as an overlay on tungsten carbide tools, thicknesses of up to 0.002" have been applied on steel compressor blading. Its very good adherence and erosion resistance makes it attractive as a gun barrel materials concept.

There is some question regarding the minimum temperature at which TiC can be deposited. Most of the available data indicate 1000-1100°C is necessary. These temperatures would make the process impractical for coating gun barrels. However, there is other proprietary information that TiC coating processes of about 500-600°C were used to coat some of the compressor blading materials. Research should be conducted and aimed at applying TiC at these lower temperatures.

The strong tendency for clean metals to adhere when operating in sliding contact is frequently reduced by use of cutting fluids which contaminate the sliding surfaces and hence prevent adhesion and galling. Some of the extreme pressure additives used in cutting fluids might prove useful if a spray coating were to be used at the breech end of a gun between firings or if it would be possible to coat the outside surfaces of shells with suitable boundary or solid lubricants.

The rate of tool wear is proportional to about the 20th power of the temperature for a high speed steel tool and to about the 10th power of the temperature for a carbide tool. This suggests that strong cooling should be beneficial in metal cutting operations and in fact this is usually the case provided the tool remains buried in the cut (as in a turning operation). However, when a cutting edge cuts

intermittently (as in a milling operation) use of a coolant makes things worse if the tool material is tungsten carbide. This is due to the formation of thermal fatigue cracks that result from the thermal stresses that arise as the tool is alternately heated and cooled. High speed steel tools that cut intermittently are helped by strong cooling since this class of tool materials is ductile enough to avoid cracks due to thermal shock and thermally induced fatigue. This experience suggests that the life of a gun barrel might be extended by use of mist cooling between firings if a high speed tool steel liner were used but probably not if a sprayed layer of tungsten carbide were to be used.

3. Casting, Forging and Extrusion Technologies

Industrial practices used in casting, forging and extrusion of various metallic materials that might provide information relevant to the gun tube erosion problem have been reviewed. (References 1-5). A typical recent contribution is given in reference 21.

Practices used for permanent mold and die castings, forging, including high energy rate forging (HERF), and extrusion incorporate a mold or die coating in nearly all cases. Such coatings are of two general types - insulating and lubricating - with some coatings performing both functions. A number of types of mold coatings are used, depending on the specific practice. Sodium silicate plus kaolin, fireclay, metal oxides, diatomaceous earth, whiting (chalk), soapstone, mica and talc are examples of insulating types of coatings. Graphite, soot, oil-containing materials, greases and other carbonaceous materials, and molybdenum disulfide are types of coatings used for lubrication purposes. Molten glass, such as used in the Ugine-Sejournet process for extrusion, is used both as a lubricant and an insulator.

In all of these metal forming and shaping processes, the selection of mold or die material and of the coating system have been developed to give good quality formed or shaped parts along with acceptable mold or die life. The mold or die life can vary considerably...from as little as only a few pushes on certain extrusion dies, to more than a quarter of a million parts produced in permanent mold cast dies, for example.

For dies and molds that run hot, more highly alloyed tool steels are the usual mold or die materials. Generally the hotter the temperature reached by the mold or die, the shorter its life because of greatly increased abrasive wear, cracking and heat checking, and erosion.

In spite of the wide diversification of types of mold or die materials, coatings, and types of metals processed, a feature common to all of these processes is that the coating system employed acts to prevent metal-to-metal contact

between the casting or work piece and the mold or die. When the coating systems fail and metal-to-metal contact occurs, mold or die life can be exceedingly short.

The conditions of gun tube erosion appear to produce a more severe and complex operating environment than most, if not all, of the industrial metal casting, forging and extrusion practices. However, there are several items from the technology of these many and varied metal forming and shaping operations that might be applied to the gun barrel erosion problem. One of these is a development of a coating system that will provide the most effective barrier between the projectile and gun tube to avoid metal-to-metal contact. Another is the selection of materials with higher hot strength, and abrasive resistance in the form of either inserts or possible surface coatings, for use in the most critical areas of erosion in the gun barrels. Another possibility that is not generally a feature of the materials and coating systems used for casting, forging and extrusion but that could be an important aid in improving life of gun barrels would be the use of gun tube materials or surface coatings that would provide improved resistance to the chemical corrosion and oxidation aspects of the gun tube erosion mechanism.

4. Rocket Nozzles[22, 23, 24, 25, 26]

In the unrealized hope that sufficient parallels exist between the conditions existing in rocket nozzles and in gun tubes, this field was surveyed. There are two separate problems - Liquid Fuels and Solid Fuels. With liquid fuel, erosion does not seem to be a problem although some corrosion may be involved. Cooled metal throats are often used in which tubes form the throat and the fuel acts as a coolant. Steel, Nb, coated Nb, and Be have been used. SiC and C inserts are also used. Ablative throats which involve controlled erosion are used (in the Apollo system for example). Materials with high specific heat and heat of vaporization are desirable. Phenolics reinforced with carbon or Quartz fibers and Poco graphite which recedes slowly are two of the materials employed.

Solid fuel rockets often use carbon or graphite inserts which are resistant to erosion. Here it is said that the stoichiometry and ignition conditions are critical. Presumably this is to maintain the carbon in a reducing atmosphere.

All of this, while not completely unrelated to gun tubes, does not suggest useful solutions.

5. Gas Turbine Engines

The burner and turbine in gas turbines are subject to oxidation and selective chemical attack (sulfidation) as a result of high gas flow rates at elevated temperatures. This problem is kept under control by the use of inherently oxidation-resistant materials (nickel or cobalt base alloys containing chromium), the use of (usually) aluminide coatings, and designs to incorporate cooling of the metal. Important differences from gun barrels are in the sizes of the parts, and the easy justification for the use of expensive alloys.

A cursory survey of the technical status of the industry indicates that past improvements have been made largely on an empirical basis. An understanding of the basic phenomena, such as oxidation or sulfidation under the existing conditions, is just beginning to be obtained. Operating conditions are sufficiently different that any direct transfer of technology so as to reduce gun barrel erosion seems unlikely. However, it is recommended that basic theoretical understanding now being obtained by the gas turbine industry be monitored for possible application to the gun erosion problem. Technology transfer, if it eventuates, would be most likely from industrial gas turbines, which operate in industrial atmospheres and use fuels containing contaminents such as sulfur.

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